A UNIQUE APPROACH TO DETERMINING THE TIME-DEPENDENT IN SITU STRENGTH OF COAL PILLARS

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ABSTRACT

In general, it cannot be assumed that the strength of coal pillars remains constant over long periods of time. Field observations indicate that a coal seam, especially when it contains a parting layer, deteriorates over time, reducing the load-bearing capacity of the pillars. This paper discusses a unique approach to determining the time-dependent strength of coal pillars in the field. Three coal pillars that were developed 5, 15, and 50 years ago were chosen for the study. Holes were drilled in coal and parting layers in each pillar, and the strength profiles were determined for each hole using a borehole penetrometer. The strength data were treated statistically to establish time-dependent strength equations for different layers. The results can be used to help estimate the loss of pillar capacity over time.

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INTRODUCTION

All manmade structures deteriorate over time; pillars in underground coal mines are no exception. There are numerous examples of coal pillars failing many years after they were developed. Scrutiny of existing pillar design theories indicates that few make any attempt to consider the effect of time. Similarly, there is rarely an attempt to consider the inhomogeneous nature of most coal seams. For example, the classic pillar design methodology involves the following three steps:

1. Calculate the vertical stress on the pillar:

$$S_v = \frac{\gamma H (W + W_e)(L + W_e)}{(WL)}, \tag{1}$$

where S_v = vertical stress,

γ = unit weight of the overburden,

H = depth of the seam,

W = pillar width (minimum pillar dimension),

L = pillar length (maximum pillar dimension),

and W_e = entry width.

2. Calculate the pillar strength using Bieniawski's formula [Bieniawski 1992]:

$$S_p = S_1\left(0.64 + \left(0.36\,\frac{W}{h}\right)\right), \tag{2}$$

where S_p = pillar strength,

S_1 = in situ seam strength,

and h = seam height.

3. Calculate the stability factor (SF) as

$$SF = \frac{\text{Pillar strength}}{\text{Pillar stress}} = \frac{S_p}{S_v}. \tag{3}$$

The stability factor that is calculated using equations 1-3 assumes that—

- The coal strength is constant and does not deteriorate over time; and
- Coal seams are homogenous.

Back-analyses of subsidence above abandoned mines using the classic methodology have found that pillar failures have occurred over a broad range of stability factors [Marino and Bauer 1989; Craft and Crandall 1988]. The implication is that over time the standard pillar design methodology loses its ability to accurately predict the strength of coal pillars.

One recent South African study focused on the phenomenon of pillar scaling over time [van der Merwe 1998]. Twenty-seven case histories of pillar failure, occurring as long as 15 years after mining, were included in the database. Three parameters were found to be statistically significant: coal seam, pillar height, and time to failure. The study concluded that the scaling rate decreases exponentially over time and further hypothesized that "the inner portions of the pillar, being protected from the atmosphere, would then weather at a lower rate."

This paper describes a detailed study of the time-dependent structural deterioration of coal pillars and proposes a means to estimate the strength reduction of the coal seam in situ by taking into account the seam heterogeneity.

FIELD OBSERVATIONS

A survey conducted by West Virginia University, Department of Mining Engineering, of room-and-pillar mines in the eastern Appalachian region found that some of the coal seams contain one or more mudstone or claystone layers with variable thicknesses [Tsang et al. 1996]. For example, the Pittsburgh and Twin Freeport Seams contain parting layers in the coal seam. During field visits to several coal mines developed in these seams, the conditions of many pillars in worked-out districts, some as much as 100 years old, were visually inspected. Most of the pillars did not show any apparent sign of instability because of their large size compared to their depth (stability factors ranged from 2 to 12).

A more detailed inspection revealed several kinds of weathering actions on the different layers of the coal seam with varying degrees of severity. The following structural deteriorations were noticed on older pillars:

• Conversion of mudstone/claystone layer to clay due to prolonged exposure to the mine moisture;

• Squeezing of the softer parting layer by the top and bottom portion of the coal;

• Major peeling of the parting layer;

• Separation of the parting from the host coal along the slick interfaces (perhaps the result of differential slippage); and

• Minor peeling of the top and bottom portion of the coal.

Figure 1 illustrates this deterioration in the structure of a pillar.

From the field observations, it was concluded that the structural deteriorations in both coal and parting are dependent on time. From these observations, aided by some laboratory studies and finite-element modeling [Biswas 1997], it was possible to postulate a conceptual model of the time-dependent strength profiles in the coal and parting layers (figures 2 and 3). Its assumptions are that—

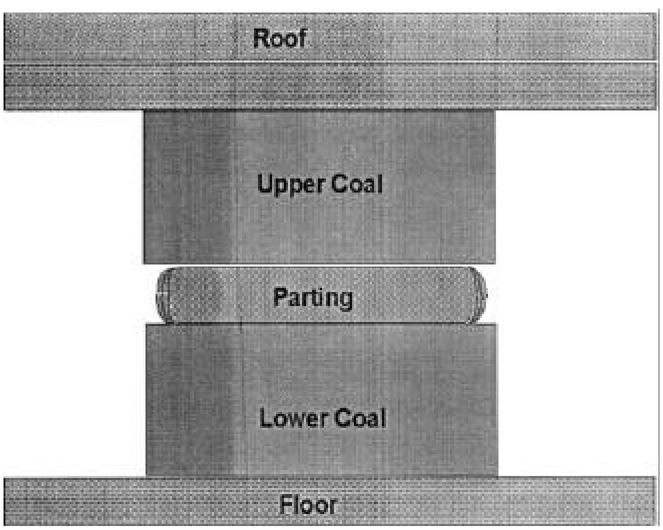

Figure 1.—Peeling of weathered parting in coal seam.

• The pillars are not affected by any mining activity in their vicinity; and

• The majority of the yield zones depicted in figures 2 and 3 are the result of the weathering action on the different layers in the pillar.

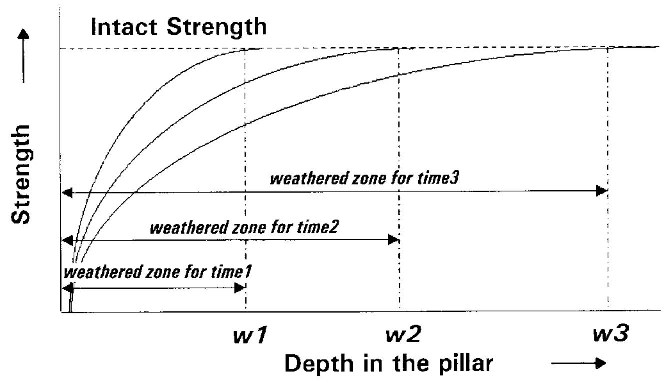

Figure 2.—Conceptualization for strength deterioration for parting. (Note: time1 < time2 < time3.)

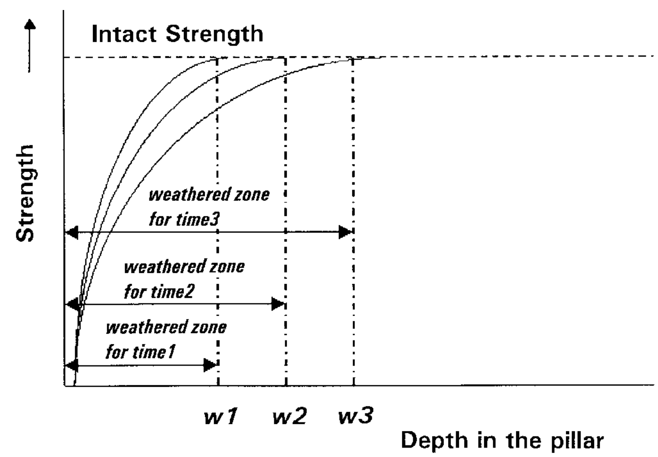

Figure 3.—Conceptualization for strength deterioration for coal. (Note: time1 < time2 < time3.)

IN SITU DETERMINATION OF TIME-DEPENDENT STRENGTH

The goal of this study was to determine one set of time-dependent strength profiles under in situ conditions. A detailed testing program was designed to establish the strength reduction in various layers of a pillar in situ over time.

THE STUDY SITE

The study was conducted at the Safety Research Coal Mine at the National Institute for Occupational Safety and Health's (NIOSH) Pittsburgh Research Laboratory. The Safety Research Coal Mine was selected for the following reasons:

• The overburden depth is very shallow, ranging from 15 to 18 m (50 to 60 ft); thus, any deterioration of the pillars is attributable to the effect of weathering rather than stress.

• The mine is developed in the Pittsburgh Seam, and it contains a parting of varying thickness (from 0.15 to 0.3 m (6 to 12 in)).

• The mine has accessible pillars developed as recently as 1991 and as long ago as the 1940s.

• The mine remains more or less inactive in terms of mining activities.

Three pillars were chosen in the mine based on their current conditions and the thickness of the parting. The three pillars were developed 5, 15, and 50 years ago. Due to other technical difficulties, more faces could not be chosen for this experiment. Figure 4 shows the mine plan and the location of the study sites.

THE APPARATUS

A borehole penetrometer (BPT) was used to measure the strength profiles in the coal and parting layers. The basic principle followed by the BPT is to fracture the borehole wall by means of an indenter and record the pressure that initiates the first fracture [Hladysz 1995]. The recorded failure pressure is then converted by a formula to determine the uniaxial compressive strength (UCS) at that location in the borehole. The BPT's great advantages are that the rock strength is tested in situ, and multiple tests can be conducted within a single borehole [Zhang et al. 1996].

The BPT consists of the following components:

- Head
- Hydraulic pump with oil reservoirs and pressure transducers
- Displacement indicator
- Four-wire electric cable
- High-pressure hydraulic hose with quick couplers
- Set of extension rods

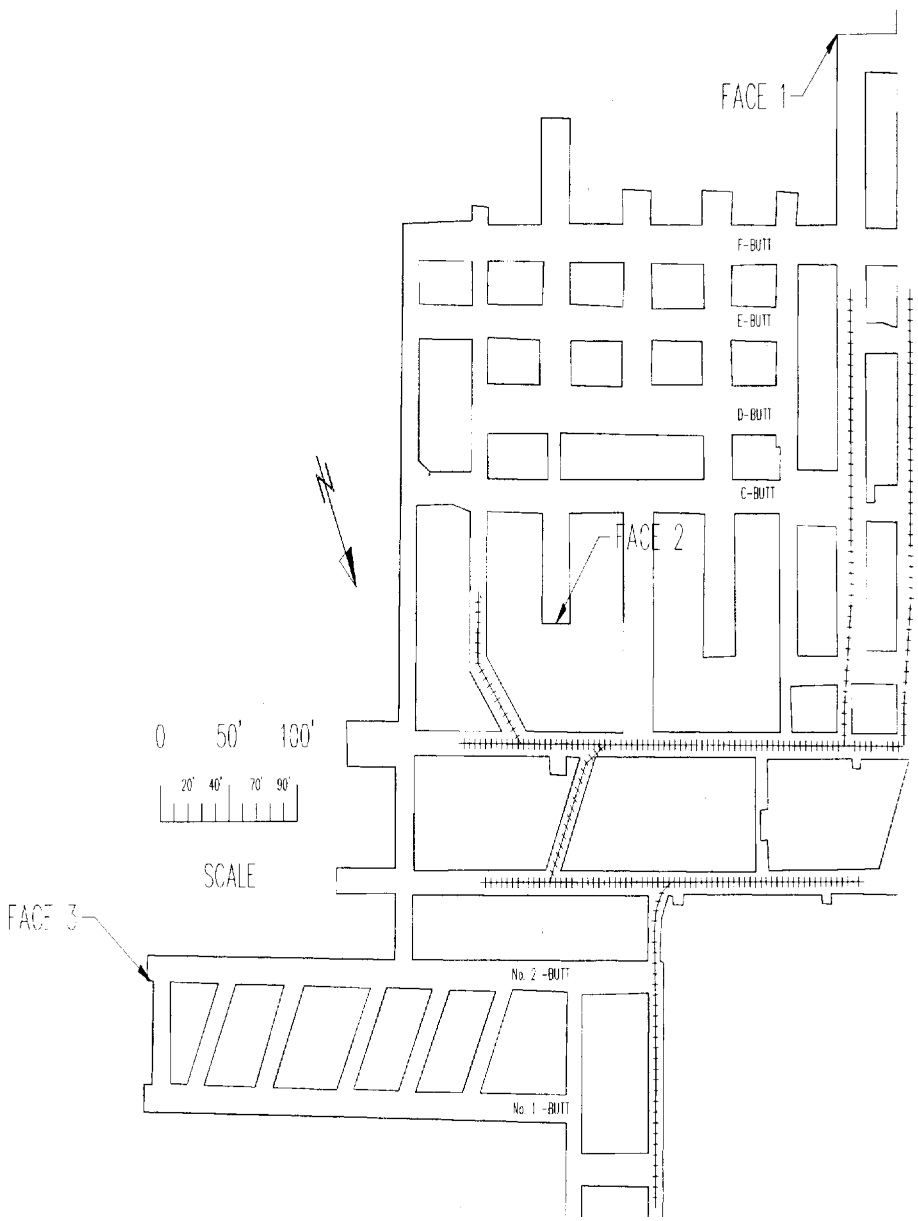

Figure 4.—Mine plan indicating three faces chosen for the BPT tests.

The BPT test setup is illustrated in figure 5. To perform the test, the head of the device is inserted into a standard NX drill hole with the help of a set of extension rods. When the head is positioned at the desired depth, the indenter is forced into the borehole wall using the hydraulic pump. At the critical pressure, the indenter penetrates the rock rapidly, making a small crater around the indenter's tip. This event is indicated by a rapid movement of the needle on the displacement indicator and by a sudden drop in pressure (figure 6). In hard and brittle rock, an audible sound is often associated with rock failure. The critical pressure causing the rock to break is a function of rock separation resistance (or penetration resistance). Penetration resistance is proportional to the material properties of the rock mass and the state of stresses. By repositioning the head and repeating the test procedures along the entire length of the hole, a penetration profile (or strength profile) for the tested section of the rock mass can be determined.

To achieve accuracy, a pressure transducer, a data acquisition module, and a digital readout unit are used. The failure pressure and ram displacement data recorded at a specified time interval are stored during an individual test and later transferred to a computer to determine the failure pressure. A portable battery-operated recorder unit records the collected data. The pressure transducer that is connected to the hydraulic pump generates the pressure signal; the displacement signal comes from a linear variable differential transformer (LVDT) that is linked to the indenter. The recorded data are stored in the data logger unit memory and later played back using a personal computer driven by application software. The data from a typical BPT test include the pressure, displacement of ram or indenter, time and an identification for the hole No., test depth, test date, etc. More details about the instrument, its specifications, principles, and testing procedure can be found elsewhere [Hladysz 1995].

THE EXPERIMENT

For each BPT test, the following steps were conducted:

1. Connect the hydraulic hoses to the head and to the pump.
2. Connect the cable to the head and to the data acquisition displacement input terminals.
3. Connect the cable to the pressure transducer and to the data acquisition pressure input terminals.
4. Set up the recording session parameters in the data logger unit (e.g. date, ID No., etc.).
5. Insert the head into the borehole and position the device at the desired depth.
6. Close the main valve of the pump.
7. Initiate a data recording session.
8. Increase pressure slowly at a constant rate, continuing to pump until failure occurs.
9. Open the valve to allow the indenter to retract fully and stop recording.
10. Reposition the penetrometer head and repeat steps 4 to 9.

Two NX boreholes were drilled in each test pillar, one in coal and one in the parting. The holes were each 3 m (10 ft) long. About 15-20 tests were conducted along each borehole. The testing frequency was higher near the pillar edge; it was postulated that the rib edge would be more disturbed than the intact central portion of the pillar. All of the data for each test were collected in the storage module during the tests and later transferred to a computer for more detailed analysis. The data for each test point were manipulated in a spreadsheet program; finally, a graph was plotted for each test point. The graph consists of time on the X-axis, failure pressure on the primary Y-axis, and the relative displacement rate of the indenter on the secondary Y-axis. Typical graphs for the parting and the coal are shown in figures 6 and 7, respectively. The failure pressure in the hard rock, in general, is characterized by a distinct jump (increase) in the ram displacement.

DATA ANALYSIS

The first step in analyzing the data was to determine the failure pressures at all test points. Then, the following conversion formula was used to convert the failure pressure to the UCS:

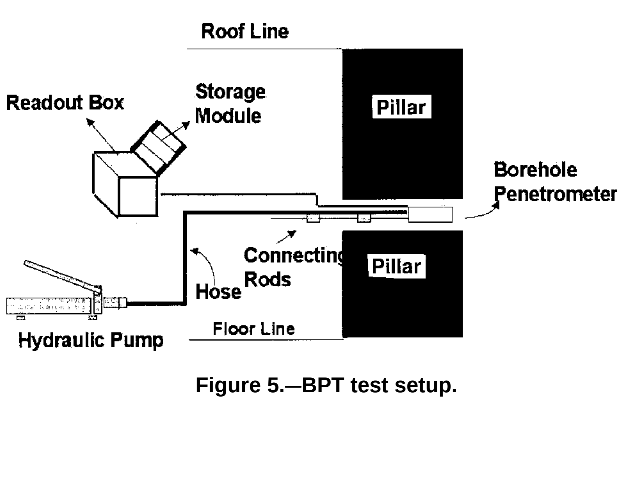

Figure 5.—BPT test setup.

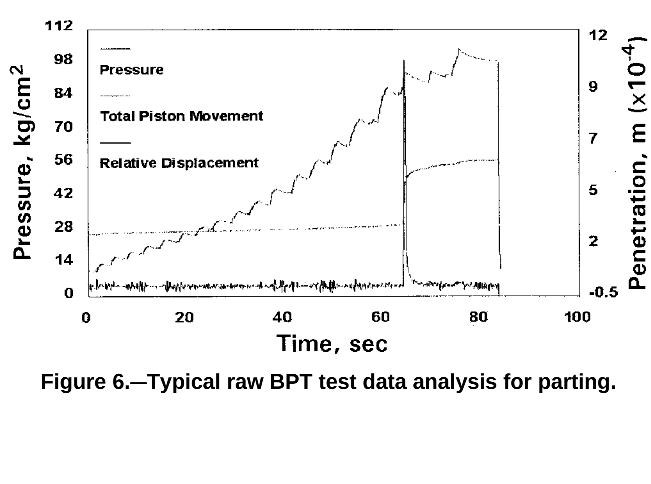

Figure 6.—Typical raw BPT test data analysis for parting.

$$UCS = (F_s)P_f\,, \tag{4}$$

where F_s = strength factor,

and P_f = failure pressure from the BPT test.

For coal, the value of the strength factor was 1.25, as suggested by Zhang et al. [1996]. For the parting, a value of 1.00 was used based on laboratory studies of the cores of the parting obtained from the BPT test holes [Biswas 1997].

The scatter plots of the converted strength values were obtained for each hole in each face. Because these scatter plots showed considerable variability in the trend of the strength deterioration, which is a typical characteristic of any experiment conducted in situ, a curve-fitting program called Curve Expert was used to fit the best curve with the highest correlation coefficient. Figures 8-10 illustrate the best-fit curves for the parting, and figures 11-13 illustrate the best-fit curves for the coal for all three faces.

The general form of all of the best-fit equations for both coal and parting is

$$y = a(1.01 - e^{-bx})\,, \tag{5}$$

where a and b are the coefficients,

y is the failure pressure or the strength,

and x is the depth (in this case, the range is from 0.06 to 3 m (0.2 to 10 ft).

The negative exponential and its negative power give the best-fit curves their asymptotic form. The correlation coefficients for the best-fit equations for the parting and coal for each age group are 0.84, 0.85, 0.89 and 0.96, 0.88, 0.94, respectively.

For the parting, the gradient in the weathered zone for the younger face is initially steeper, but the slope flattens as the age increases. This change in strength gradient before it reaches the intact or stabilized strength is considerable. The weathered zone apparently expands from 1 to 3 m (3.2 to 10 ft) over the 50 years. For coal, the strength gradient for all of the age groups is steeper than that of the parting, and the expansion of

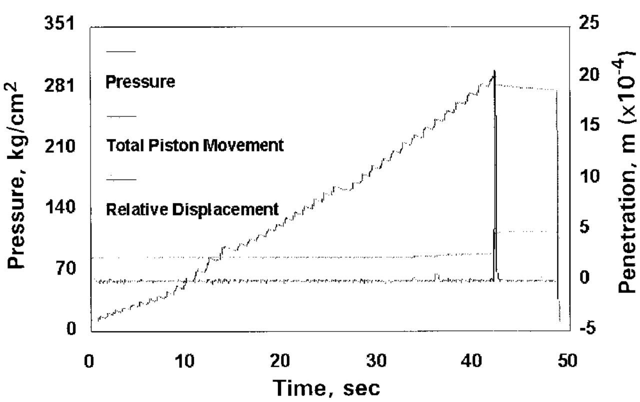

Figure 7.—Typical raw BPT test data analysis for coal.

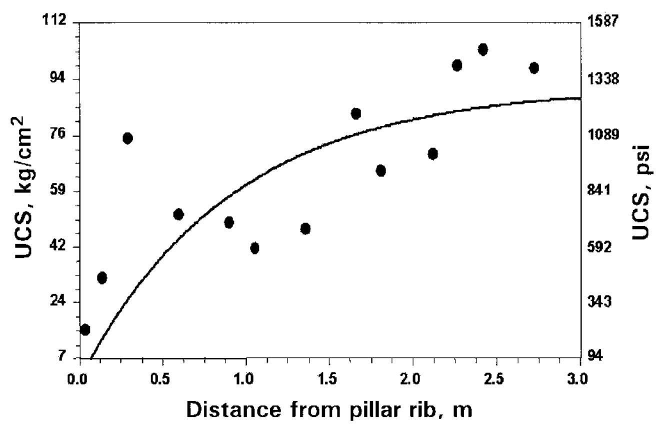

Figure 9.—Best-fit curve for 15-year-old parting.

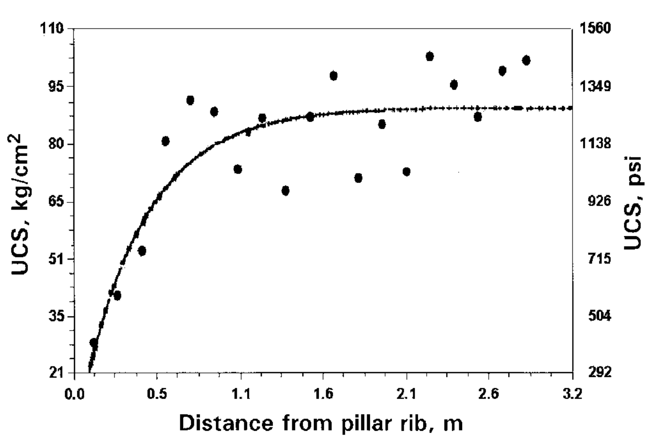

Figure 8.—Best-fit curve for 5-year-old parting.

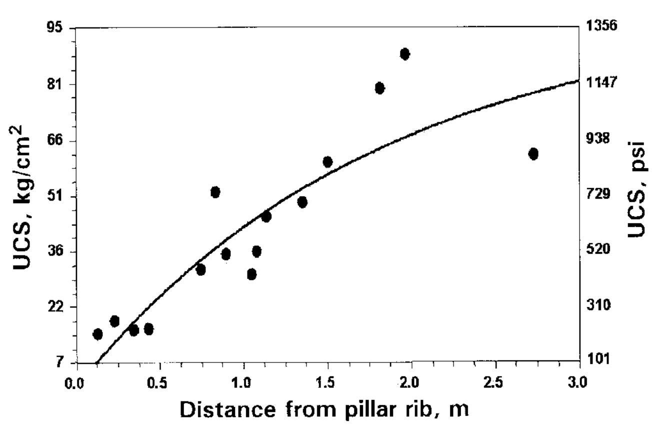

Figure 10.—Best-fit curve for 50-year-old parting.

the weathered zone is much less (from 0.2 to 1 m (0.7 to 3.2 ft)). These findings fit the conceptual model of the strength degradation for parting and coal over time described earlier.

Figures 8-13 also indicate that there is some borehole-to-borehole variability in the intact strength measured in the interior of the pillars for both the coal and the parting. This variability may be attributed to natural variability between the three different faces. In order to generalize the results, the data from each borehole were normalized to the measured intact strength. The normalized strength curves are shown in figures 14 and 15.

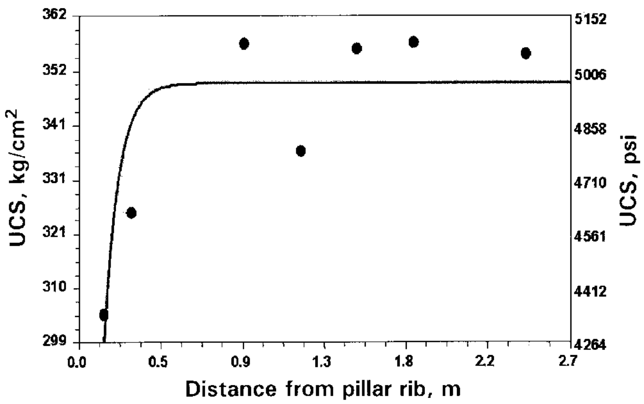

Figure 11.—Best-fit curve for 5-year-old coal.

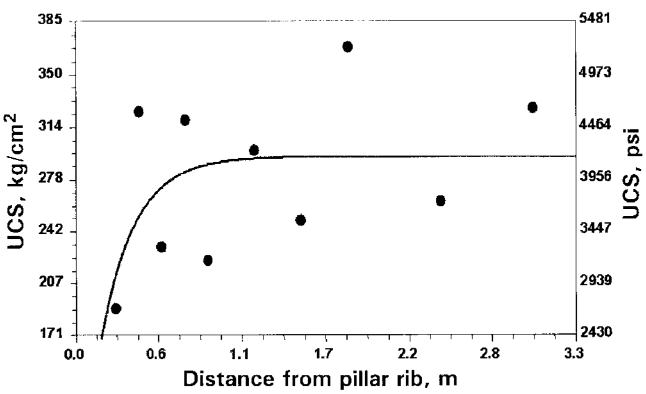

Figure 12.—Best-fit curve for 15-year-old coal.

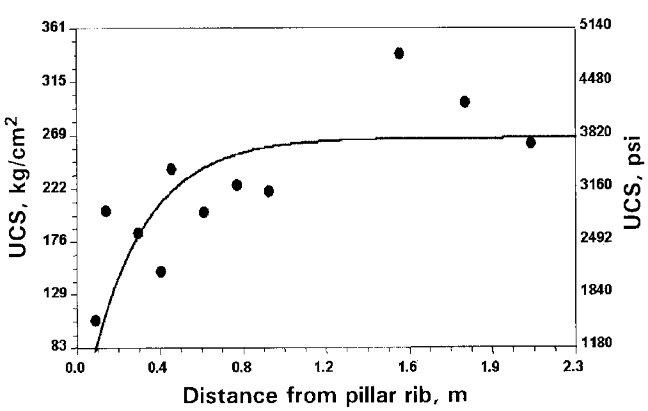

Figure 13.—Best-fit curve for 50-year-old coal.

FORMULATION OF TIME-DEPENDENT STRENGTH DETERIORATION

The BPT data can be used to derive a time-dependent strength formula for the pillars in the study. Using the best-fit equations shown in figures 14-15, data sets were generated for each material for all three ages. The data sets were generated for the depth ranges from 0.06 to 3 m (0.2 to 10 ft). No data could be generated right at the ribline because no BPT tests were conducted there. A nonlinear regression analysis was conducted on these data sets separately for the coal and for the parting with two independent variables (time and depth) and one dependent variable (strength). A freeware software called NLREG34 was used to perform the nonlinear regression. Equation 6 is the stress gradient for the parting, and equation 7 is the final equation for coal:

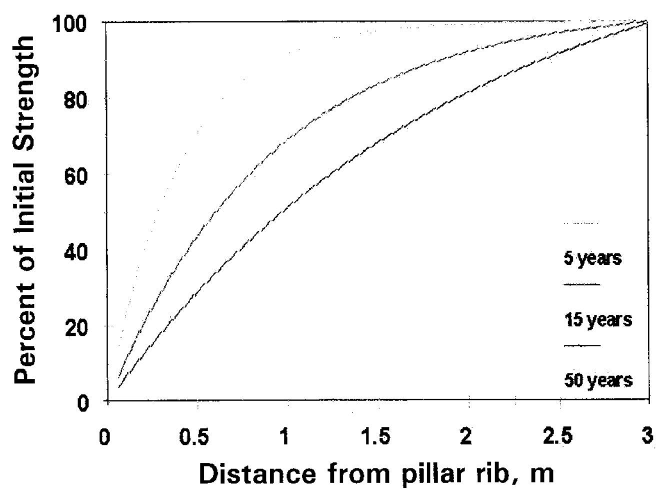

Figure 14.—Time-dependent strength deterioration for parting.

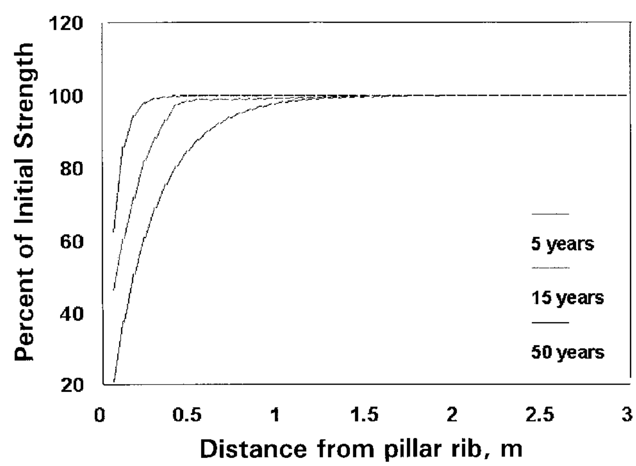

Figure 15.—Time-dependent strength deterioration for coal.

$$\%\ \text{parting strength} = 100\,(1.01 - e^{-0.5\,D}) - 0.45t \qquad (6)$$

$$\%\ \text{coal strength} = 100\,(1.01 - e^{-3.5\,D}) - 0.13t \qquad (7)$$

where D = depth into the rib, ft,

and t = time after mining, years.

In these equations, the strength is defined as a percent of the original intact compressive strength that is assumed to be constant in the core of the pillar. Near the rib, the strength is a function of the distance from the rib (depth) and the time after mining. The relationship between the strength and the depth is a negative exponential, but that between strength and time is linear.

Unfortunately, applying these time-dependent strength equations to predict the strength of full-scale pillars is not simple. Three issues are foremost:

1. *Effect of parting thickness:* If the parting is the pillar's weakest layer, as in this study, then a thicker parting would be expected to result in a weaker pillar.
2. *Effect of parting on confining stress within the pillar:* Most of the load-bearing capacity of a coal pillar is due to the development of confining stress within the pillar's core. Studies have shown that many pillars contain weak layers of clay or friable coal, but their effect on overall pillar strength is ambiguous [Mark and Barton 1996].
3. *Nonlinear effect of time:* In reality, the rate of strength degradation probably decreases with time, as suggested by van der Merwe [1998]. Because this study included only three pillars, it was difficult to quantify the nonlinear relationship between time and strength.

Nevertheless, if the limitations of the necessary assumptions are kept in mind, it is possible to use the strength gradient equations to shed light on the possible effects of time on coal pillar stability. The following example illustrates one possible approach. The key assumption is that *at any particular time, the distance from the actual pillar rib and the depth at which the strength is 60% of the intact strength will be considered as the width of the portion of the weathered zone that is not capable of carrying any load and thus transfers the load on the intact portion of the pillar*. The effect of this assumption is that the pillar's strength is decreased over time as the width-to-height ratio diminishes, whereas the applied stress increases as the pillar's load-bearing area is reduced.

To calculate the time-dependent stability factor, the following steps are followed:

1. Calculate the original stability factor using equations 1-3.
2. Determine the strength profile at a specified time using equation 3 or 4, and determine the depth of weathering (where the strength is 60% of the intact).
3. Calculate the resultant pillar width by subtracting the depth of weathering from the original pillar width.
4. Recalculate the applied stress using equation 1 and the new pillar dimensions.
5. Use equation 2 to determine the new pillar strength and equation 3 to calculate the reduced stability factor at the specified time.
6. Repeat this process to determine the approximate lifespan of the pillar.

For example, assume the following parameters:

- The overburden depth is 244 m (800 ft).
- The pillar is a square pillar with a 15.2-m (50-ft) dimension.
- The seam height is 1.8 m (6 ft).
- The entry width is 6.1 m (20 ft).
- The in situ seam strength is 6.2 MPa (900 psi).

Because the parting is the weakest layer of the seam in this case, to be on the conservative side, equation 6 (for the parting) is used to determine the strength profile and also the width of yielded zone due to the weathering process. From a statistical point of view, it is recommended that equations 6 and 7 be used within the same time range as the original field data used in their development, i.e., 5 to 50 years [Myers 1990].

Figure 16 illustrates the changes in strength and applied stress over time. Where the two curves meet, at time = 35 years, the stability factor is 1.0, which means that the pillar has a 50% chance of failing before that time.

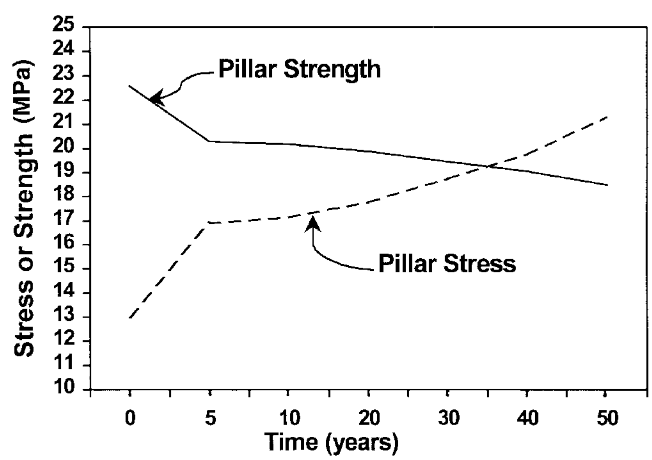

Figure 16.–Safety factor reduction over time.

CONCLUSIONS

The use of the BPT to measure the in situ time-dependent strength is the unique feature of this study. It generated a set of in situ strength data in a relatively simple field-testing program. The in situ data were used to develop time-dependent strength equations for coal and parting layers. An example case was used to demonstrate the use of these equations in predicting the change of stability factor over the years.

The parting material weathered much more rapidly than the coal. This implies that much of the observed between-seam variability in long-term pillar strength may be due to the presence or absence of partings in the coal. However, this study only addressed a single type of parting material within a single coal seam. Much work remains before the effect of time on coal pillar strength is fully understood.

ACKNOWLEDGMENTS

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